TELKOMNIKA Telecommunication Computing Electronics and Control
Vol. 20, No. 2, April 2022, pp. 437~446
ISSN: 1693-6930, DOI: 10.12928/TELKOMNIKA.v20i2.22835

Comprehensive study of current trend of the remotely operated vehicle for underwater systems

Fauzal Naim Zohedi, Mohd Shahrieel Mohd Aras, Hyreil Anuar Kasdirin
Underwater Technology Research Group (UTeRG), Center for Robotics and Industrial Automation (CERIA), Fakulti Kejuruteraan Elektrik, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal, Melaka, Malaysia

Article Info

Article history:

Received Oct 15, 2020
Revised Jan 27, 2022
Accepted Feb 04, 2022

Keywords:

Remotely operated vehicle
ROV controller
ROV modelling
System identification

ABSTRACT

This paper aim to provide a basic fundamental knowledge for researchers on underwater remotely operated vehicle (ROV) system and current trend of ROV controller. The vehicle is used for exploration, investigation or inspection of underwater environment as a replacement of human due to human limitation. It can dive deeper than human and can be manoeuvred into hazard environment. In this paper, the basic development and classification of ROV is discussed. The modelling of ROV, manoeuvrability and controller designed by researchers since 1990 also being discussed. It is expected that this paper will help readers in doing research on the controller of ROV.

Corresponding Author:

Fauzal Naim Zohedi
Underwater Technology Research Group (UTeRG), Center for Robotics and Industrial Automation (CERIA), Fakulti Kejuruteraan Elektrik, Universiti Teknikal Malaysia Melaka
76100 Durian Tunggal, Melaka, Malaysia
Email: fauzal@utem.edu.my

1. INTRODUCTION

Earth is covered with 71% of water. Among all of the water, 96% of it is ocean or saline water. Underwater exploration has become more and more important day by day. The exploration study of the underwater environment important for scientific purpose [1], sustainability of ocean [2] and for commercial purpose. One of the scientific underwater studies is underwater geological study where it is important to predict tsunami from plate movement underwater. For commercial purpose, underwater study is done to find oil and gases.

To study underwater environment, human has its limitation. The maximum depth can be explored by human with very high-tech equipment is 700 meters by using atmospheric diving suit (ADS). It is a human suit underwater armour used for underwater scientific exploration. To go deeper, remotely operated vehicle (ROV) is introduced. ROV can dive up to more than 3000-meter depth. The used of ROV will eliminate limitation of human and also provide safe solution for underwater exploration. In this paper, ROV system and controller will be reviewed to ease researcher in designing ROV controller.

2. ROV SYSTEM

ROV is an abbreviation that stand for remotely operated vehicle. The vehicle operated in underwater environment for exploration, investigation or inspection. It is important as a replacement of human to do underwater job for the sake of safety. It has the ability to dive deeper than human and also can be

manoeuvred into hazard environment. As it is remotely operated, it is classified under unmanned underwater vehicle (UUV) category. Under the same UUV category, there is also autonomous underwater vehicle (AUV) which pre-programmed used for underwater mapping. The study of underwater wireless communication is a hot topic as AUV manoeuvre on its own [3]. Differ to ROV, it is linked up (tethered) with operator who control the vehicle via direct wire that call umbilical cord. These wires will supply the power for the ROV and also act as communication link for ROV operator. Figure 1 shows the basic component of ROV [4].

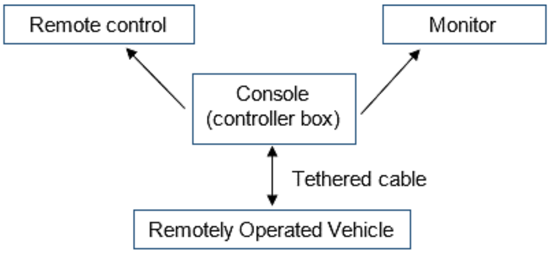

Figure 1. ROV basic component

The ROV can be classified into three category which are observational class ROV (OCROV), mid-size ROV (MSROV) and work class ROV (WCROV). All these three classifications are based on size and the function of it. The OCROV typically weight below 100 kg and dive up to 300 m while MSROV and WCROV weight above 100 kg and dive more than 300 m depth [4].

To maneuver a ROV, hydrodynamic factor of ROV need to be considered. This depends on the shape of the ROV. For an autonomous underwater vehicle (AUV) the long and slim shape is applied to ensure low drag for speed purpose but do not have high stationery capabilities. For ROV used for inspection and observation which move slower, high stationery capability is important. The short shape and open frame offered high stationery capability and low drag. The stationery of ROV is controlled by numbers of thruster fixed in the ROV itself [4].

The most common issues of ROV are power source, degree of autonomy and communication linkage. The power source can be from surface, vehicle itself or hybrid (combination of both). For degree of autonomy, it can be human, autonomous or hybrid (both human and autonomous). For communication linkage, it can be the cable used, acoustical, sensors, and optical [1].

ROV operational environment can be fresh water, salt water or murky water. The performance of the ROV depends on the density of the water (fresh water 1000 kg/m3 and salt water 1035 kg/m3) and the water flow. The more density, the more pressure given to the ROV and the more drag force happen. The drag force also increases as the velocity of ROV increases. Double the velocity, quadruple the drag value. For the water flow, the higher the flow of water the harder to maintain stationery of ROV. The flow of water in ocean or ocean dynamic are divided into two which are horizontal current and vertical tide. These current and tide will affect the surge, sway, heave, pitch, roll and yaw of ROV [1]. These six degree of freedom [5] is shown in Figure 2.

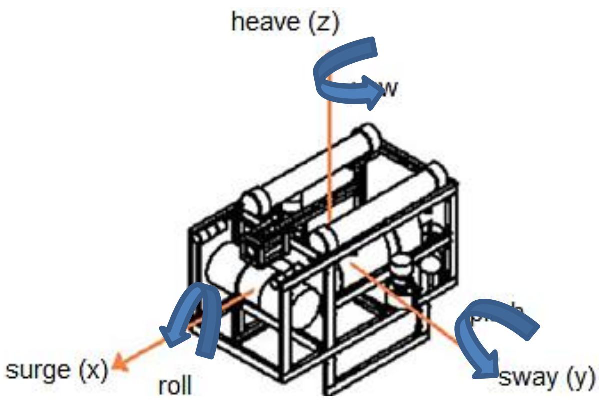

Figure 2. Six degree of freedom of ROV

The ROV stability is based on positive stability concept where it is based on stability of pitch and roll. Centre of gravity plays important role in the stability of ROV. Thrusting ROV to certain depth will affect centre of gravity of ROV as it shifts the center of gravity to the top of ROV. This directly affect its stability. The mean length ratio to mean width of ROV and thruster placement also affect stability of ROV. The bigger ratio of length to width, and the further away thruster from centre of ROV, the better stability to ROV.

The stability of ROV also affected by drag on the ROV and the tethered wire. The drag can be skin friction; friction on body of ROV or form friction; friction to the cross-sectional area of the ROV. The most drag happens to ROV coming from the tethered cable as the tethered length become longer. Figure 3 shows the drag of ROV system versus length of ROV [1].

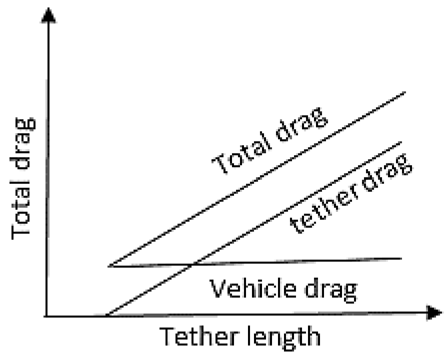

Figure 3. Drag of ROV system versus tether length

For manoeuvring of ROV is based on the propulsion system. There can be three thruster version, four thruster version and five version. The ROV must have high thruster to drag ratio to ensure good manoeuvrability and stability. ROV uses direct current (DC) motor as its thruster motor. To manoeuvre forward, reverse, dive and surface, H bridge system is implemented. Figure 4 shows the basic operation of the H bridge system [1].

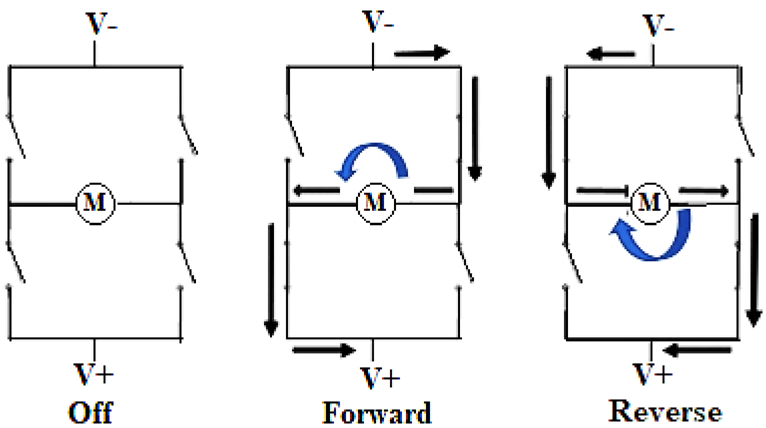

Figure 4. basic operation of H bridge system

ROV is equipped with lots of sensors based on the task need to be done. The basic sensors used for manoeuvring are cameras, pressure sensor and initial measurement unit (IMU). These sensors are used to locate position of the ROV and observed the water environment. Pressure sensor is used to measure depth or heave, while IMU sensor is used to measure orientation of ROV.

ROV is very important in the underwater industries and marine activities. The task to be completed by ROV has become more challenging and complex. ROV operator need to have ability to handle two tasks simultaneously; manoeuvring and manipulation of manipulator. These lead to design and development of automatic control for holding position of ROV. Operator can focus on manipulation while the system will

autonomously control the ROV at certain position and depth. Due to this, accurate modelling of ROV is important to design and simulate the control system of ROV. The model of ROV is very complex where it will be based on the ROV itself and also based on its environment (hydrodynamic).

3. ROV MODELLING

Modelling of ROV can be done in two ways: mathematical modelling and system identification. For mathematical modelling, all dynamic condition of the ROV need to be considered. Figure 5 shows the dynamic of ROV system.

The ROV model is based on coordinate system. The six degree of freedom is described as vector $v = [u\ v\ w\ p\ q\ r]^T$: u for surge, v for sway, w for heave, p for roll, q for pitch, and r for yaw. The basic ROV mathematical modelling based on Euler angle transformation is shown in (1) [6], [7]. The model is a nonlinear model.

$$M\dot{v} + C(v)v + D(v)v + g(\eta) = B(v)u \tag{1}$$

Where:

M = 6 x 6 inertia matrix (rigid body mass and added mass)
$C(v)v$ = matrix of Coriolis and centripetal forces
$D(v)v$ = hydrodynamic damping matrix
$g(\eta)$ = vector force and moment (hydrostatic)
$B(v)$ = 6×3 control input matrix

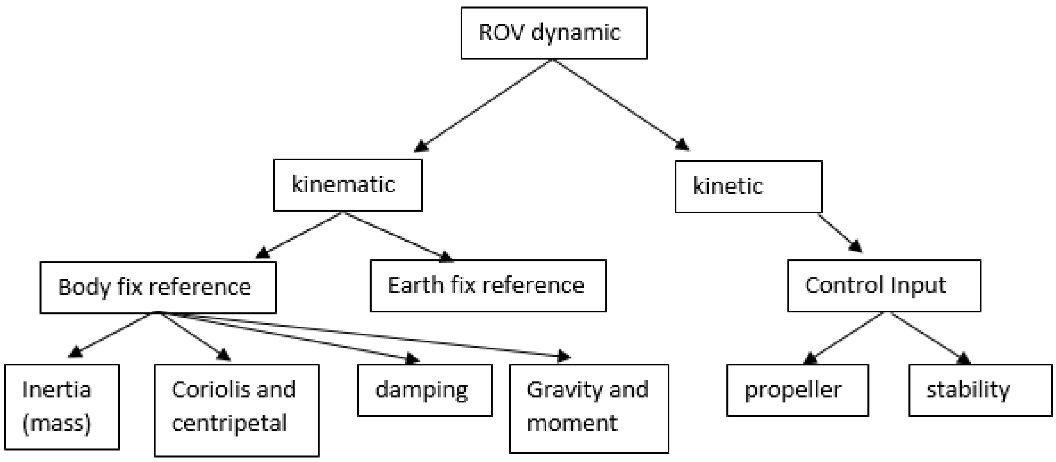

Figure 5. ROV system dynamic

Some researchers made assumetion to reduce the complexity of the mathematical modelling based on the designed of ROV [8]. Aras *et al.* [8] assumed that sway role and pitch are negligible for depth control of ROV. The matrix for mass and inertia, M_{RB} was shown as (2) with the assumption that the developed ROV was symmetrical.

$$M_{RB} = \begin{bmatrix} m & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & I_Z \end{bmatrix} \tag{2}$$

The hydrodynamic damping, *D(V)* was simplified as (3).

$$D(V) = \begin{bmatrix} X_U + X_{U|U|}|U| & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & Z_w + Z_{w|w|}|w| & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & N + N_{r|r|}|r| \end{bmatrix} \quad (3)$$

The gravity, G and buoyancy, B shown in (4) below while force and torque vector shown in (5) and (6). The position matrix, L and thruster vector, U indicate the force and torque of the ROV

$$G = \begin{bmatrix} 0 \\ 0 \\ B \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (4)$$

$$L = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 \\ a & b & c & d \\ e & f & g & h \end{bmatrix} \quad (5)$$

$$U = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix} \quad (6)$$

The position vector was based on the thruster placement in the ROV from its center of gravity. The mapping matric is shown in Figure 6.

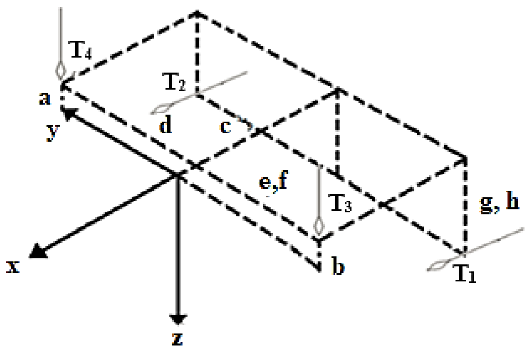

Figure 6. The mapping matrix, L

To design ROV model based mathematical modelling, researchers need to face high complexity of mathematics, lots of unknown parameters and lots of assumption need to be made. Another way to get the model of ROV with less complexity of mathematic is using system identification. For system identification, the motion of ROV is being tested experimentally. A prototype of the ROV need be made and real time experimental of the motion studied need to be tested.

For system identification, 5 steps need to be considered. The steps are observation and data gathering, model structure selection, model estimation, model validation and model application [8]. Start with system observation and data gathering, ROV system is observed and the data is gathered. Two sets of data are needed; training and validation data. The input given to ROV system can be pulse, steps, random binary sequence (RBS), pseudo random binary (PRBS), m-level pseudo random (m-PRS) and multi-sine.

Once data was gathered, model structure is selected. It can be artificial neural network (ANN) or black box method, auto regressive with exogenous input (ARX) or auto regressive moving average with exogenous input (ARMAX). Then, the selected model structure is implemented for model estimation and

model validation to generate a ROV model. Lastly, the model generated is used to design ROV controller. Figure 7 shows an example of input output graph simulation data for system identification purpose. The input given to the system is multi-sine.

In order to select the best model, Aras and Abdullah [5] compare the mathematical modelling and system identification method. The output result shows both the transient respond are acceptable. The author used system identification result for controller design because it has considered disturbance and environmental factor.

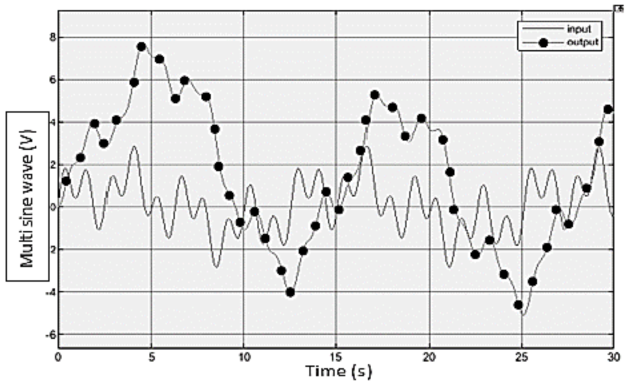

Figure 7. Input-output of the ROV system for depth control

4. ROV CONTROLLER

ROV controller is important for precise trajectory, position tracking and safety purpose [2]. Many researches had been done to control the ROV position from proportional, integral and derivative (PID) based controller to artificial intelligent based controller. Due to highly non-linear model of ROV, the design of controller is very tough. In this review, ROV controller for positon control is being reviewed.

ROV suffered from high overshoot when dive or surface from certain level. This overshoot can lead to damage to the ROV because it can get hit to coral reefs, rock or ocean floor [8]. To eliminate this, [9], [10] has designed PID controller, PID with continuous input smoother (CIS-PID) and fuzzy-PID controller for ROV depth system. The result shows PID controller has overshoot while CIS-PID and fuzzy-PID controller shows exceptional result. Fuzzy PID shows faster response with a bit oscillation before steady state achieved. Similar study also conducted in [11], [12] using fuzzy-PID to suppress overshoot. A simulation also shows promising result. Zanoli and Conte [9] also state that sliding mode control (SMC) and artificial neural network (ANN) were not implemented because SMC could result jitter and affect the accuracy of the system while ANN could lead to lag phenomenon of the ROV because parameters were revised by online learning.

Goheen and Jefferys [13] multivariable self-tuning autopilots for autonomous and remotely operated underwater vehicles had been designed. The main purpose of the system was to ensure effectiveness of underwater intervention that strongly linked to ROV’s ability to maintain at certain position or auto positioning. It is very tough because the ROV’s vessel dynamics were strongly couple and difficult to derive [13]. The simulation result shows multivariable self-tuning autopilot control can be used successfully to control the ROV. Sebastían [14], implemented adaptive fuzzy sliding mode controller (fuzzy-SMC) to a snorkel underwater vehicle. The fuzzy-SMC was introduced to cope with lack of precise mode. Fuzzy controller was adopted due to its ability to adapt with water perturbation. Experiment conducted in a small tank shows fuzzy-SMC were capable to compensate the dynamic and perturbation of water. It concluded that, the requirement of precise model was reduced with the fusion of fuzzy in the controller. Hoang and Kreuzer [15] also implemented adaptive controller to control an underwater vehicle (UV). The model of the underwater vehicle was developed by using multibody system approach. It considered the UV and also the umbilical cable in the model design. Then, recursive back stepping method is implemented as adaptive controller. It estimated the umbilical cable force and choose the right power for thrusters. The simulation shows good result and able to simulate large scale of UV motion.

Bessa *et al.* [16] use similar method as [14], similar fuzzy-SMC controller to control the depth of ROV. The paper compare fuzzy-SMC with traditional SMC and applied Lyapunov stability theory to prove its stability. The result shows fuzzy-SMC has superior result with no chattering effect. Lamas *et al.* [17] implement a hybrid approach to design UV control system. It implements ANN to generalize complex nonlinear model of ROV from discrete set of sample. The controller was then implement to a submersible

catamaran. The result shows a precise behaviour towards positioning and orientation set point without concerning complicated nonlinear models of ROV plan. Aras *et al.* [18], also implement ANN based controller. The controller calls neural network predictive control (NNPC). The NNPC was compared with PI controller, single input fuzzy logic controller (SIFLC), linear quadratic regulation (LQR) controller and improved SIFLC. The result shows NNPC superior in terms of settling time but lost in terms of computational time.

Salim *et al.* [6] analysed the implementation of fuzzy and proportional derivative (PD) controller for ROV depth control. Transient response of both controller was studied in terms of time rise (Ts) and steady state error. Both shows exceptional result but fuzzy controller shows faster response. Ishaque *et al.* [19] upgrade the conventional fuzzy logic controller (FLC) to SIFLC to control ROV position. The main reason for this upgrade was to provide easier controller design and less computational time with similar good result. The SIFLC only uses single input while conventional FLC (CFLC) uses two input. The data set for SIFLC for designing also lesser then CFLC. As a result, SIFLC shows similar good result as CFLC with much lesser computational time and easier to design. Aras and Abdullah [5], upgrade the SIFLC to adaptive simplified fuzzy logic controller (ASFLC) to get better controller result to ROV depth control. The SIFLC and ASFLC were compared using transient response of the system. Simulation and experimental result shows ASFLC was superior to SIFLC in term of peak time (Tp), rise time (Tr), settling time (Ts) and overshoot (%).

Joseph *et al.* [20] the motion and position control of ROSUB 6000 was analysed. Controller algorithm used to control the motion and position was reverse dynamic task theory. Three angular motion were considered; heading, pitch and roll. Disturbance had been applied to the ROV and the algorithm proven to be able to correct its targeted heading angle at ± 2 deg angle. Wang *et al.* [21], use time delay estimation with non-singular terminal sliding mode (NTSM-TDE) to control the depth of ROV. This paper compare NTSM-TDE with linear TDE method. The author compares the tracking error and the tracking performance between these two controllers. The result shows both controller can be used to control ROV but NTSM-TDE shows better result.

Chen *et al.* [22] use bio inspired SMC to control the depth of ROV. The designed controller able to eliminate chattering effect and also compensate constructed disturbance. It shows that the controller had the ability to adapt with the perturbation of water. Wahyuddin *et al.* [23] was doing comparison of several controllers for depth control of ROV. The controllers were, PID, Mamdani-FLC (M-FLC), adaptive neural fuzzy inference system (ANFIS) and SIFLC. All of these controllers were implemented to a model of developed ROV. The model of the ROV was gained using system identification method. The results were analysed using transient response. For time rise (Tr), SIFLC shows the most superior, followed by PID, M-FLC and ANFIS. For percent overshoot (% OS), M-FLC shows the most superior, followed by SIFLC, ANFIS and PID.

Huang and Yang [24] apply double loop SMC (DSMC) with novel switching control to control WCROV. The loops were inner loop for velocity control and outer loop for position control. DSMC was compared with the SMC and fuzzy sliding mode control (FSMC). Haima ROV was used to simulate the result. DSMC able to reduce overshoot with precise control and suppressed chattering effect of SMC. It also able to cope with perturbation of water.

All of controller discusses previously used thruster to move to certain depth and hold its position. Another way of controlling the depth of ROV is flexible ballast tank. Aras *et al.* [25] investigate about the possibility of using flexible ballast tank to hold at certain depth. The surfaced to bottom and bottom to surface task was experimented. The result shows the ROV's depth can be controlled by flexible ballast tank. It has slow rise time compared to common thruster system but fast settling time.

5. SUMMARY OF ROV CONTROL SYSTEM

There were many controllers designed to track the position and depth of ROV from conventional PID controller to artificial intelligent controller. 90% of discussing paper use thruster control to navigate from surface to bottom or from bottom to surface. Only 2 papers discussed ROV controller is based on flexible ballast tank. This is due to the availability of ROV thruster in ROV designed. The uses of ballast tank will make the ROV bulky and has limitation to certain depth where the pressure of water change every 10 meter depth of water. In terms of getting positive stability for ROV at initial condition, the ballast tank can be used but the design of the tank must be very robust as it goes deep in the water. For thruster control for depth, the limitation of depth is counter by current supply to the thruster. For navigation purpose, thruster will be used. Table 1 below summarized all controller discussed previously.

From Table 1, it shows that the research of ROV controller never stop since 1990 until now and still enhancing. Many controllers had been developed to solve position control of ROV. The aim of the controller is to get the best position tracking, best depth position or best holding position to east underwater exploring job. Lots of the designed controller only done in simulation and each designed controller shows possibilities to be

implemented to real system. The differences were the applied ROV model, assumption make for modelling and the water condition concern in the designed model. Many approaches had been done to analyse the performance of ROV control. Some using control errors, some using input errors, some using transient response of the system and many more. To compare and decide the best controller, it required to have a specific ROV and a specific need. Simulation result should be brought to the real implementation situation to validate the simulation and get the best result.

Table 1. Summary of ROV controller

Year	Title	Method	Result
1990	Multivariable self-tuning autopilots for autonomous and remotely operated underwater vehicles	Multi-input/multi output (MIMO) self-tuning controllers	Successfully cntrol the ROV
2000 and 2003	Remotely operated depth control	PID and fuzzy used and step response is studied	- PID controller result an overshoot - PID-CIS eliminate overshoot but slow time response - FUZZY-PID-eliminate overshoot but a bit oscillation before stable
2006	Adaptive fuzzy sliding mode controller for the snorkel underwater vehicle	fusion of a robust or sliding mode controller and an adaptive fuzzy system	AFSM able to compensate the dynamic problems and perturbations of underwater vehicle
2008	Depth control of remotely operated underwater vehicles using an adaptive fuzzy sliding mode controller	adaptive fuzzy sliding mode controller is proposed to regulate the vertical displacement	The AFSM improve the conventional SMC result
2009	A hybrid approach for designing the control system for underwater vehicles	neural network based controllers for operating a submersible catamaran	The submersible catamaran are able to compensate perturbation force and have precise tracking behaviour
2010	A robust of fuzzy logic and proportional derivative control system for monitoring underwater vehicles	PD and fuzzy logic transient responds	Fuzzy logic has better time rise compare to PD controller
2010	Single input fuzzy logic controller for unmanned underwater vehicle	Single input fuzzy logic controller (SIFLC) compare with conventional two-input FLC (CFLC) to a single input single output (SISO) controller	SIFLC result is similar to CFLC. The advantages of SIFLC is only one parameter need to be tuned.
2010	A fuzzy-PID depth control method with overshoot suppression for underwater vehicle	fuzzy controller calculates the PID controller parameters	Non overshoot depth control was gained
2012	Development and modelling of unmanned underwater remotely operated vehicle using system identification for depth control	Implemented PID controller for newly developed ROV	Exceptional result shown
2015	Adaptive simplified fuzzy logic controller (ASFLC) for depth control of underwater Remotely operated vehicle	Adaptive simplified fuzzy logic controller and single input fuzzy logic controller (SIFLC) was compared	Simulation and experimental result shows ASFLC result was better than SIFLC
2015	Depth control of an underwater remotely operated vehicle using neural network predictive control (NNPC)	NNPC was compare with conventional PI controller, linear quadratic regulation (LQR) and FLC	NNPC shows superior result in terms of settling time but high computational time
2015	Depth control of ROVs using time delay estimation with non-singular terminal sliding mode	Non-singular terminal sliding mode (NTSM) control method based on time delay estimation (TDE)	both NTSM-TDE and linear TDE can be used for ROV depth control but NTSM- TDE shows better result
2016	Bio-inspired sliding mode controller for ROV with disturbance observer	ROV control input was controlled by bio-inspired sliding mode control theory and disturbance observer	Bio-inspired sliding mode controller able to eliminate the chattering effect of traditional sliding control algorithm
2018	Comparison of controllers design performance for underwater remotely operated vehicle (ROV) depth control	Single input fuzzy logic controller (SIFLC), adaptive neural fuzzy inference system (ANFIS), mamdani fuzzy logic controller (M-FLC) and proportional integrated differential (PID) controller were compare	- For Tr = lead by SIFLC, PID, M-FLC and ANFIS - For % OS = lead M-FLC, SIFLC, ANFIS and PID
2019	Double-loop sliding mode controller (DSMC) with a novel switching term for the trajectory tracking of work-class ROVs	DSMC was compared with traditional SMC and fuzzy sliding mode control (FSMC)	DSMC reduced overshoot and compensate chattering effect

6. CONCLUSION

ROV is very important in the underwater industries for underwater exploration for scientific purpose and commercial purpose. The main issue of ROV are the controlling of the ROV where it requires an accurate and precise modelling to ensure precise result. The model of ROV is very complex because of the ROV itself and its working environment (hydrodynamic). The uncertainty of the environment also plays major role to control ROV. ROV have 6 degree of freedom that couple together that make it more difficult to model and also affected by tethered cable. Mathematical modelling of ROV need to have lots of assumption, simulation parameters data and experimental data to get a precise model. To cater the modelling complexity, system identification was introduced to get the model of the ROV. This approach is experimental based. It is way easier and approximation made is proven acceptable. This approach also considered the environmental condition because approximation made via experimented data. Once the model is gained, controller can be designed. Many controllers had been designed to control the ROV since 1990 until now and keep enhancing. The controller was designed based on the specific ROV model. Analysis being made using input errors, control errors and transient response. Lots of controller design was in simulation and not tested in the real situation. As the simulation result looks promising, it should be validated in the real situation to get the best result. This paper provides readers basic understanding of ROV system, modelling of ROV system and current trend on ROV controllers. It will guide readers in doing research on the controller of ROV where all fundamental knowledge is presented in this paper.

ACKNOWLEDGMENT

Authors wish to express our gratitude to honorable university, Universiti Teknikal Malaysia Melaka (UTeM). Special appreciation and gratitude to especially for Centre of Research and Innovation Management (CRIM), Center for Robotics and Industrial Automation (CERIA) for supporting this research and to Faculty of Electrical Engineering from UTeM for supporting this research.

REFERENCES

[1] Ø. Ødegård, A. J. Sørensen, R. E. Hansen, and M. Ludvigsen, "A new method for underwater archaeological surveying using sensors and unmanned platforms," *IFAC-PapersOnLine*, vol. 49, no. 23, pp. 486-493, 2016, doi: 10.1016/j.ifacol.2016.10.453.

[2] J. Wu, S. Guo, H. Huang, W. Liu, and Y. Xiang, "Information and Communications Technologies for Sustainable Development Goals: State-of-the-Art, Needs and Perspectives," in *IEEE Communications Surveys & Tutorials*, vol. 20, no. 3, pp. 2389-2406, thirdquarter 2018, doi: 10.1109/COMST.2018.2812301.

[3] G. Li, J. Wu, T. Tang, Z. Chen, J. Chen, and H. Liu, "Underwater acoustic time delay estimation based on envelope differences of correlation functions," *Sensors (Switzerland)*, vol. 19, no. 5, pp. 1-11, 2019, doi: 10.3390/s19051259.

[4] R. D. Christ and R. L. Wernli, *The ROV Manual: A User Guide for Remotely Operated Vehicles: Second Edition*. 2013.

[5] M. S. M. Aras and S. S. Abdullah, "Adaptive simplified fuzzy logic controller for depth control of underwater remotely operated vehicle," *Indian Journal Geo-Marine Sciences (IJMS)*, vol. 44, no. 12, pp. 1995-2007, 2015.

[6] M. A. Salim, A. Noordin, and A. N. Jahari, "A Robust of Fuzzy Logic and Proportional Derivative Control System for Monitoring Underwater Vehicles," *2010 Second International Conference on Computer Research and Development*, 2010, pp. 849-853, doi: 10.1109/ICCRD.2010.187.

[7] T. I. Fossen and A. Ross, "Nonlinear modelling, identification and control of UUVs," *Advances in Unmanned Marine Vehicles*, no. 7491, pp. 13-42, 2006, doi: 10.1049/PBCE069E_ch2.

[8] M. S. M. Aras, S. S. Abdullah, M. Z. A. Rashid, A. A. Rahman, and M. A. A. Aziz, "Development and modeling of unmanned underwater remotely operated vehicle using system identification for depth control," *Journal of Theoretical and Applied Information Technology*, vol. 56, no. 1, pp. 136-145, 2013. [Online]. Available: http://www.jatit.org/volumes/Vol56No1/16Vol56No1.pdf

[9] S. M. Zanoli and G. Conte, "Rov Depth Control," *IFAC Proceedings Volumes*, vol. 33, no. 21, pp. 251-255, 2000, doi: 10.1016/s1474-6670(17)37083-0.

[10] S. M. Zanoli and G. Conte, "Remotely operated vehicle depth control," *Control Engineering Practice*, vol. 11, no. 4, pp. 453-459, 2003, doi: 10.1016/S0967-0661(02)00013-8.

[11] Z. Tang, Luojun, and Q. He, "A fuzzy-PID depth control method with overshoot suppression for underwater vehicle," *Life System Modeling and Intelligent Computing*, vol. 6329 LNCS, no. PART 2, pp. 218-224, 2010, doi: 10.1007/978-3-642-15597-0_24.

[12] C. Yu, X. Xiang, F. Maurelli, Q. Zhang, R. Zhao, and G. Xu, "Onboard system of hybrid underwater robotic vehicles: Integrated software architecture and control algorithm," *Ocean Engineering*, vol. 187, p. 106121, 2019, doi: 10.1016/j.oceaneng.2019.106121.

[13] K. R. Goheen and E. R. Jefferys, "Multivariable self-tuning autopilots for autonomous and remotely operated underwater vehicles," in *IEEE Journal of Oceanic Engineering*, vol. 15, no. 3, pp. 144-151, July 1990, doi: 10.1109/48.107142.

[14] E. Sebastían, "Adaptive fuzzy sliding mode controller for the snorkel underwater vehicle," *Lecture Notes in Computer Science*, vol. 4095 LNAI, pp. 855-866, 2006, doi: 10.1007/11840541_70.

[15] N. Q. Hoang and E. Kreuzer, "Modelling and adaptive control of an underwater vehicle system: A multibody system approach," *IUTAM Symposium on Fluid-Structure Interaction in Ocean Engineering*, vol. 8, pp. 105-116, 2008, doi: 10.1007/978-1-4020-8630-4_10.

[16] W. M. Bessa, M. S. Dutra, and E. Kreuzer, "Depth control of remotely operated underwater vehicles using an adaptive fuzzy sliding mode controller," *Robotics and Autonomous Systems*, vol. 56, no. 8, pp. 670-677, 2008, doi: 10.1016/j.robot.2007.11.004.

[17] A. Lamas, F. L. Peña, and R. J. Duro, "A hybrid approach for designing the control system for underwater vehicles,"

Hybrid Artificial Intelligence Systems, vol. 5572 LNAI, pp. 88-95, 2009, doi: 10.1007/978-3-642-02319-4_11.
[18] A. F. N. A. Mohd Aras, M.S. Abdullah, S. S. Abd Aziz, and M. A. Rahman, "Analysis of an improved Single Input Fuzzy Logic Controller designed for depth control using Microbox 2000/2000c interfacing," *International Review of Automatic Control*, vol. 6, no. 6,pp. 728-733, 2013.
[19] K. Ishaque, S. S. Abdullah, S. M. Ayob, and Z. Salam, "Single input fuzzy logic controller for unmanned underwater vehicle," *Journal of Intelligent and Robotic Systems*, vol. 59, no. 1, pp. 87-100, 2010, doi: 10.1007/s10846-010-9395-x.
[20] M. S. Joseph, M. A. Atmanand, G. A. Ramadass, R. Raju, and V. K. Jayakumar, "Navigation and position control of underwater vehicle ROSUB 6000," *Communications in Computer and Information Science*, vol. 103 CCIS, pp. 25-32, 2010, doi: 10.1007/978-3-642-15810-0_4.
[21] Y. Wang *et al.*, "Depth control of ROVs using time delay estimation with nonsingular terminal sliding mode," *OCEANS 2015 - MTS/IEEE Washington*, 2015, pp. 1-6, doi: 10.23919/OCEANS.2015.7401804.
[22] W. Chen, Y. Wei, H. Liu, and H. Zhang, "Bio-inspired sliding mode controller for ROV with disturbance observer," *2016 IEEE International Conference on Mechatronics and Automation*, 2016, pp. 599-604, doi: 10.1109/ICMA.2016.7558631.
[23] M. Wahyuddin, N. Azmi, M. Shahrieel, M. Aras, M. Khairi, and M. Zambri, "Comparison of Controllers Design Performance for Underwater Remotely Operated Vehicle (ROV) Depth Control," *International Journal of Engineering & Technology*, vol. 7, no. 2.14, 2018.
[24] B. Huang and Q. Yang, "Double-loop sliding mode controller with a novel switching term for the trajectory tracking of work-class ROVs," *Ocean Engineering*, vol. 178, pp. 80–94, 2019, doi: 10.1016/j.oceaneng.2019.02.043.
[25] M. S. M. Aras, L. W. Teck, F. A. Azis, A. S. M. Nor, and N. Hasim, "Comparison of depth control form surface and bottom set point of an unmanned underwater remotely operated vehicle using PID controller," *Jurnal Teknologi*, vol. 74, no. 9, pp. 105–111, 2015, doi: 10.11113/jt.v74.4813.

BIOGRAPHIES OF AUTHORS

Fauzal Naim Zohedi was born in Pulau Pinang, Malaysia in 1984 and graduated from department of Electrical and Electronic Engineering, Universiti Malaysia Pahang in 2008. He received his Master of Engineering (Industrial Electronics and Control) from Universiti Malaya in 2012. In 2008 to 2009 he was working as Device Engineer at ON Semiconductor, Senawang, Malaysia. He serves as a lecturer at Universiti Teknikal Malaysia Melaka (UTeM) from 2012 until 2019. Currently he is doing his Ph.D at Universiti Teknikal Malaysia Melaka (UTeM). His research interest covers control, instrumentation, automation, fuzzy application and underwater robotic. He can be contacted at email: fauzal@utem.edu.my.

Mohd Shahrieel Mohd Aras owned both his Electrical Engineering Diploma and Degree from Universiti Teknologi MARA (UITM). Next, he persued both master and Ph.D at Universiti Teknolgi Malaysia (UTM). Currently he serves as Associate Professor at Universiti Teknikal Malaysia Melaka (UTeM). He is also Head of Mechatronics Department and Chair of IEEE Oceanic Engineering Society Malaysia Chapter. His research interest are Underwater Robotics, Fuzzy Logic, Neural Network, and System Identification. He can be contacted at email: shahrieel@utem.edu.my.

Hyreil Anuar Kasdirin gained his bachelor's degree from Universiti Teknologi MARA (UITM) in Electrical Engineering. Next, he pursued his master and Ph.D in control system at Sheffield University, United Kingdom. Currently he is senior lecturer and serve as Director at Center of Academic Development, Universiti Teknikal Malaysia Melaka (UTeM). His research interest are Communications, Control Engineering, Artificial Intelligence and Optimization. He can be contacted at email: hyreil@utem.edu.my.